

# charmed baryon in a Diquark model

Q. W. Wang\*

*Institute of Modern Physics,  
Chinese Academy of Science, P.O. Box 31,  
Lanzhou 730000, P.R.China*

A diquark model is used to investigate single charmed baryons. In this model, baryon is composed of two diquarks and an antiquark. Masses of lowest lying states with  $J^P = 1/2^\pm$  are obtained. Some masses are smaller than other theoretic predictions which indicates that these baryons of pentaquark structure could be relatively stable. The results also show that  $\Lambda(2882)$  may be a pentaquark with  $J^P = 1/2^-$  and  $\Xi(3125)$  may be a pentaquark with  $J^P = 1/2^+$ .

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## I. INTRODUCTION

Baryons containing heavy quarks have always been interesting. Recently many new excited charmed baryon states have been discovered by CLEO, BaBar, Belle and Fermilab. Heavy baryons have narrow widths and they are hard to produce. As products in the decays of heavy mesons or in hadron colliders, the cross sections to produce them are small. There are no resonant production mechanisms as for heavy mesons. So, heavy baryons always have been obtained by continuum production[1]. Furthermore, none of the quantum numbers, listed in the PDG book, are really measured, but are assignments based on quark model[2].

Despite these problems, the meaning to study these baryons is important. Heavy baryons provide a laboratory to study the dynamics of the light quarks in the environment of heavy quark, such as their chiral symmetry[3]. It really is an ideal place for studying the dynamics of diquark. In these baryons, a heavy quark can be used as a 'flavor tag' to help us to go further in understanding the nonperturbative QCD than do the light baryons[1]. Theoretically, the study of heavy baryons has a long story[4, 5, 6]. But, up to now, simple and reliable estimates for the experimental quantities regarding to the baryon spectroscopy, the production and decay rates are still lack. So lots of work have to be done for theorists.

At present, only for single-charmed baryons masses of ground states as well as many of their excitations are known experimentally with rather good precision. If the spectrum of the single charmed baryons is well known, it will provide us a framework for studying baryons with one bottom quark and help for understanding the doubly or triply charmed baryons. In this paper, we use the Jaffe-Wilczek [7] model to predict masses of single charmed pentaquark states with  $J^P = \frac{1}{2}^\pm$ . In the following section we introduce the diquark concept and the Jaffe-Wilczek model; In section 3 we give the mass formula and our results. In the end, a discussion will be given in section 4.

## II. DIQUARK AND J-W MODEL

The concept of diquark appeared soon after the original papers on quarks[8, 9, 10]. It was used to calculate the hadron properties. It helps us to understand hadron structure and high energy particle reactions[11]. In heavy quark effective theory, two light quarks often refer to as diquark, which is treated as particle in parallel with quark themselves. There are several phenomenal manifestations of diquark: the  $\Sigma - \Lambda$  mass difference, the isospin  $\Delta I = 1/2$  rule, the structure function ratio of neutron to proton, *et al.*[12, 13]. There are two kinds of diquark: the good and the bad diquark. The good diquark is more favorable energetically than the bad, which is indicated by

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\*Electronic address: 9685233@163.com

quantum numbers	Flavor	Color	Spin	Orbital
good diquark	$\bar{\mathbf{3}}_a$	$\bar{\mathbf{3}}_a$	$s = 0_a$	$l = 0_s$
bad diquark	$\bar{\mathbf{6}}_s$	$\bar{\mathbf{3}}_a$	$s = 1_s$	$l = 0_s$
2 diquarks $P = +1$	$\bar{\mathbf{6}}_s$	$\bar{\mathbf{3}} \times \bar{\mathbf{3}} \rightarrow \mathbf{3}_a$	$s = 0_s$	$l = 1_a$
$P = -1$	$\mathbf{3}_a$	$\bar{\mathbf{3}} \times \bar{\mathbf{3}} \rightarrow \mathbf{3}_a$	$s = 0_s$	$l = 0_s$

TABLE I: Summary of the diquark quantum numbers. The two quarks obey Fermi statistics while the diquarks do Bose. The subscripts  $a$  and  $s$  are antisymmetric and symmetric for short.

both the one-gluon exchange and instanton calculations. In  $SU(3)_f$ , the good diquark has flavor-spin symmetry  $\bar{\mathbf{3}}_F \bar{\mathbf{3}}_S$  while the bad  $\bar{\mathbf{6}}_F \mathbf{6}_S$ . To give a color singlet state, both kinds of diquark have the same color symmetry  $\mathbf{3}_C$ . Two diquarks obey Boson statistic while two quarks in a diquark obey Fermi statistic. Jaffe and Wilczek used only the good diquark in their paper[7].

Jaffe and Wilczek's pentaquark is composed of two good diquarks and an antiquark. The two diquarks combine into a color antisymmetric  $\mathbf{3}_C$  and flavor symmetric  $\bar{\mathbf{6}}_F$  with components:  $[ud]^2$ ,  $[us]^2$ ,  $[ds]^2$ ,  $[ud][us]_+$ ,  $[ud][ds]_+$  and  $[us][ds]_+$ . In the following, we use  $[qq']$  to denote a good diquark, and  $(qq')$  a bad. The spin wave function is symmetric because the diquark has spin zero. To give a totally symmetric wave function, an orbital excitation between the two diquarks is needed which combines the spin of antiquark to give state  $J^P = \frac{1}{2}^+$  and  $\frac{3}{2}^+$ .

Two diquarks can also combine into an  $SU(3)_f$  symmetric  $\mathbf{3}_F$ , with no orbital excitation[14]. Take into the antiquark into account, we can obtain states with  $J^P = \frac{1}{2}^-$ . Jaffe and Wilczek haven't considered the  $\frac{3}{2}^+$  and  $\frac{1}{2}^-$  states in their model. In summary, we list the quantum numbers of these diquark systems in Table I.

The combination of two diquarks with an antiquark gives  $SU(3)_f$  multiplets  $\mathbf{8} \oplus \bar{\mathbf{10}}$  for flavor  $\bar{\mathbf{6}}_F$  two diquarks combination and  $\mathbf{8} \oplus \mathbf{1}$  for  $\mathbf{3}_F$ . By replacing an  $s$  quark with a  $c$  quark, we get states of charmed or hidden charmed baryons. In this paper, we only consider baryons with one charm quark and with no charmed antiquark, i.e. the single charmed baryons.

### III. MASS FORMULA AND SPECTRUM

A schematic mass formula of the pentaquark reads:

$$M = m_{D1} + m_{D2} + m_q + E_L. \quad (1)$$

Here,  $m_D$  is the diquark mass,  $m_q$  the antiquark mass and  $E_L$  the orbital exciting energy. Firstly, we consider the good diquarks. Taking the  $SU(2)$  isospin symmetry into account, we need to know the diquark mass of  $[ll']$ ,  $[ls]$  and  $[lc]$ , with  $l$  and  $l'$  being the light quarks  $u$  or  $d$ . There is no  $[sc]$  diquark, since it is obtained by substituting one  $s$  to one  $c$  quark and the diquark is flavor antisymmetric. We can get the diquark mass by adding the two quarks mass and their binding energy. Deducing from J-W's original paper, we use the parameters  $m_{[ll']} = 420 \text{ MeV}$  and  $m_{[ls]} = 580 \text{ MeV}$ . And their binding energy we show in Table II. The binding energy of  $[lc]$  can be obtained, with a coefficient  $3/4$  as in J-W's paper, from the mass difference of  $\Sigma_c(2455)$  and  $\Lambda_c(2285)$  which are composed of a diquark and an antiquark. We see in Table II that two quarks having a closer mass is more tightly bound which may be indicated by the spin-spin interaction. And the mass splitting

$$(ud) - [ud] > (us) - [us] > (uc) - [uc] \simeq 0 \quad (2)$$

is expected.

Moreover, a generalized Chew-Frautschi formula relating baryon mass to orbital angular momentum is

$$E = \sqrt{\sigma L} + kL^{-\frac{1}{4}}(m_1^{\frac{3}{2}} + m_2^{\frac{3}{2}}) \quad (3)$$

quark mass	$m_c$	$m_s$	$m_l$
	1650	460	360
diquark energy	$ll'$	$ls$	$lc$
good	420	580	1840
bad	673	680	1840
binding energy for good	300	240	130

TABLE II: Quark mass and diquark energy in unit MeV.

with  $k \approx 1.15 \text{ GeV}^{-\frac{1}{2}}$  and  $\sigma \approx 1.1 \text{ GeV}^2$  [12, 13]. Here,  $m_1$  and  $m_2$  are the diquark and quark mass respectively. In Ref.[12, 13], N(1680) with good diquark [ $ud$ ] and  $\Delta(1950)$  with bad diquark ( $ud$ ) are assigned to have angular momentum  $L = 2$ , which give the diquark mass splitting

$$(ud)^{3/2} - [ud]^{3/2} \simeq 0.28 \text{ GeV}^{3/2}. \quad (4)$$

Similarly, the mass difference of  $\Sigma(2030)$  and  $\Sigma(1915)$  lead to

$$(us)^{3/2} - [us]^{3/2} \simeq 0.12 \text{ GeV}^{3/2}. \quad (5)$$

From these diquark mass splittings we can get the bad diquark masses. In the end, all the parameters we used are listed in Table II.

If we take the ideal mixing for  $\mathbf{8} \oplus \bar{\mathbf{10}}$  and  $\mathbf{8} \oplus \mathbf{1}$  respectively, the flavor assignments of charmed pentaquarks composed of good diquark are  $[ll][lc]\bar{l}$  for  $\Sigma_c$  and  $\Lambda_c$  and  $[ls][lc]\bar{l}$  for  $\Xi_c$ . Because the mass of  $[cs]$  is unknown, we will not consider  $\Omega_c$ . Furthermore, in equation (1) we have not considered the splitting of the  $J^P = 3/2^+$  and  $1/2^+$  states. The  $1/2^+$  is generally lower in energy, so we take equation(1) as the mass formula for states  $1/2^+$ . The  $J^P = 1/2^-$  state with no orbital angular momentum is a little simpler. With a substitution of un-charmed bad diquark for good diquark, we can get more masses of single charmed baryons. Since the bad diquark is a spin triplet, we encounter the problem as before both for the  $P = \pm 1$  pentaquark. We still only take states with the lowest angular momentum. All the masses of single charmed baryons we can get are showed in Figure 1. They are 2620, 2860, 2873 and 3113 MeV for  $\Lambda_c(\Sigma_c)$ , 2780, 3020, 2880 and 3120 MeV for  $\Xi_c$ . For a comparison, the experimental data are also there.

The  $\Sigma_c$  and  $\Lambda_c$  have the same predicted masses, because we can't distinguish them when use formula 1. The lowest predicted mass with  $J^P = 1/2^-$  lies between the experimental  $P = -1$  doublet. The masses of bad diquark ( $ll'$ ) and ( $ls$ ) are so closed which leads to baryons of the same quantum numbers and with one bad diquark having almost the same mass. The predicted  $\Lambda_c(2873)$  to have  $J^P = (1/2)^-$  is coincided with an early conjecture[15] for  $\Lambda_c(2882)$ . For  $\Xi_c$ , there is one state  $\Xi_c(2790)$  near the predicted state  $\Xi_c(2780)$  with the same  $J^P = 1/2^-$ , and  $\Xi_c(3120)$  with  $J^P = 1/2^+$  is very close to experimental  $\Xi_c(3125)$ .

The masses of  $\Lambda_c(2620)$  and  $\Xi_c(2780)$  of our predictions are a little heavy than the lowest masses predicted in Ref.[1, 6]. In their papers, different symmetry or mix have led to more heavy results such as  $\Lambda(2747, 2816)$  and  $\Xi(2898, 2859)$ , which are above our predictions of baryon  $J^P = 1/2^-$  with good diquark. This means that pentaquarks may be relatively stable than some three-quark baryons. The  $\Sigma_c(2620)$  is lower a lot than other theoretic predictions with mass about 2700 MeV [1, 5, 6] which is easy to understand because in their models  $\Sigma_c$  and  $\Lambda_c$  are well to split.

Lastly, we just simply discuss decays of these baryons. The combining energy of diquark with one charm quark is relatively small. In the "fall-apart" mechanism, the dominant decay mode of these five quark objects is decaying into a three-quark charmed baryon and a  $\pi$  meson. For example, the  $J^P = \frac{1}{2}^- \Sigma_c(\Lambda_c)$  which has a mass 2620 MeV can decay into the  $J^P = \frac{1}{2}^+ \Lambda_c(2285)$  or  $\Sigma_c(2455)$ . We note that in the early paper of Copley[4] the decay of  $\Lambda_c(2510)$   $J^P = \frac{1}{2}^-$  to  $\Sigma_c(2455)$  and pion is forbidden by energy conservation.

#### IV. SUMMARY AND DISCUSSION

In this paper, we have extended the Jaffe-Wilczek's Diquark Model for  $J^P = 1/2^+$  pentaquark to dealing with charmed baryons. We have given a spectrum of  $P = \pm 1$  lowest lying charmed pen-

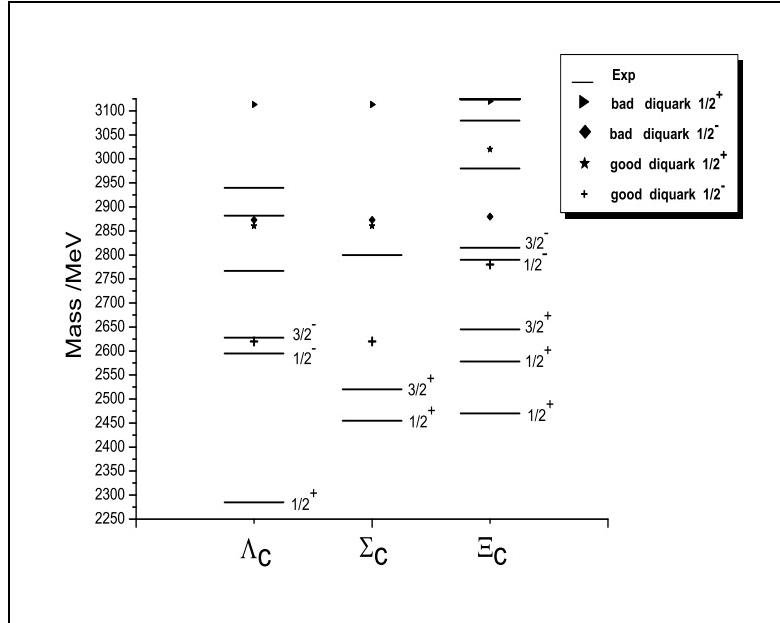


FIG. 1: The single charmed baryon spectroscopy. The 'good diquark' labels baryons having two good diquarks, while 'bad diquark', those having one good and one bad.

taurank and compared them with experimental data. We find that some states have experimental correspondences.

The mass formula we used is just schematic. It is better to include mass contribution from the Pauli blocking and annihilation effects[16]. But to quantify them is somewhat difficult. Energy contribution from Pauli blocking is conjectured to have relation  $E_{pb}^{L=0} > E_{pb}^{L=1}$  which means the two-diquark subsystem of flavor symmetry  $\mathbf{3}_F$  is heavier than the one of  $\bar{\mathbf{6}}_F$  [13, 16]. If so, states of  $J^P = 1/2^-$  will be a little heavier than our predictions.

A problem?  $M_c(1650) + M_l(360) = M_D^*(2010) < M_D(2460)$  for "the attractive one-gluon-exchange potential of a diquark in color 3-bar is a factor of 2 weaker than that of a color-singlet qq-bar".

## V. ACKNOWLEDGMENTS

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